

Magneto-gyrotropic photogalvanic effects due to inter-subband absorption in quantum wells

H Diehl¹, V A Shalygin², S N Danilov¹, S A Tarasenko³, V V Bel'kov³,

D Schuh¹, W Wegscheider¹, W Prettl¹ and S D Ganichev¹

¹*Terahertz Center, University of Regensburg, 93040 Regensburg, Germany*

²*St Petersburg State Polytechnic University, 195251 St Petersburg, Russia and*

³*A.F. Ioffe Physico-Technical Institute,*

Russian Academy of Sciences, 194021 St. Petersburg, Russia

Abstract

We report on the observation of the magneto-photogalvanic effect (MPGE) due to inter-subband transitions in (001)-oriented GaAs quantum wells. This effect is related to the gyrotropic properties of the structures. It is shown that inter-subband absorption of linearly polarized radiation may lead to spin-related as well as spin independent photocurrents if an external magnetic field is applied in the plane of the quantum well. The experimental results are analyzed in terms of the phenomenological theory and microscopic models of MPGE based on either asymmetric optical excitation or asymmetric relaxation of carriers in \mathbf{k} -space. We observed resonant photocurrents not only at oblique incidence of radiation but also at normal incidence demonstrating that conventionally applied selection rules for the inter-subband optical transitions are not rigorous.

Optical excitation of free carriers in a semiconductor can lead to generation of an electric current. In this paper we deal with the photogalvanic effects, which appear neither due to inhomogeneity of the optical excitation nor due to inhomogeneity of the sample (in the case of quantum well structure we mean in-plane inhomogeneity). Such photocurrents are caused by the asymmetry of elementary processes of photoexcitation or carrier relaxation resulting in a redistribution of carriers in momentum space. This is possible in structures of the appropriate symmetry only, in particular, gyrotropic materials give a rich spectrum of photogalvanic phenomena. In gyrotropic quantum well structures (QWs) photocurrents comprise (for a review see¹⁻³) the linear⁴ and circular⁵⁻⁸ photogalvanic effects, the linear and circular photon drag effects⁹⁻¹¹, the spin-galvanic effect due to optical excitation^{12,13}, as well as photocurrents caused by quantum interference of one- and two-photon excitation¹⁴⁻¹⁷, which represent coherent photogalvanic effects^{18,19}. These investigations explored new mechanisms of photocurrent formation and gave an experimental access to in-plane symmetry properties, spin relaxation, and details of band structure, in particular, to relativistic spin-orbit features of low-dimensional structures like Rashba and Dresselhaus spin-splitting in semiconductor quantum wells^{20,21}.

An additional root of photogalvanic effects is provided by application of an external magnetic field. The magnetic field breaks the time inversion symmetry resulting in additional mechanisms of photocurrents. For instance, in inversion asymmetric but non-gyrotropic bulk crystals like GaAs, homogeneous illumination with circularly polarized radiation does not yield a current. However, in the presence of an external magnetic field this effect becomes possible and has been detected²². Essential progress has been achieved in the generation of magnetic field induced photogalvanic effects applying visible, near-, mid- and far-infrared laser radiation (for a review see^{2,3,23}). It has been demonstrated that optical excitation of quantum well structures can result in spin photocurrents, caused by the Drude absorption due to spin-dependent asymmetric scattering²⁴⁻²⁶ or direct optical transitions between branches of the spin-split electron subband^{27,28}, as well as in photocurrents due to spin-independent diamagnetic mechanisms²⁹⁻³².

Here we present experimental and theoretical studies of photocurrents induced by inter-subband optical transitions in quantum wells in the presence of an in-plane magnetic field. The analysis gives evidence that the observed photocurrents are related to gyrotropy of quantum wells, which is caused by bulk and/or structure inversion asymmetry. We demonstrate

that the magneto-gyrotropic photogalvanic effect generated by direct transitions between size-quantized subbands is caused by a new, so far not discussed, type of spin-independent diamagnetic mechanism. We show that the current is due to \mathbf{k} -linear diamagnetic terms in the scattering amplitude which describe the relaxation of photoexcited carriers.

I. EXPERIMENTAL RESULTS

Experiments have been carried out on molecular-beam-epitaxy grown (001)-oriented n -doped GaAs/AlGaAs multiple (30 periods) QWs at room and liquid helium temperatures. Each quantum well of 8.8 nm, 8.2 nm, and 7.6 nm width contains a two-dimensional electron gas with the carrier density of $3 \cdot 10^{11} \text{ cm}^{-2}$ at 4.2 K. The quantum well widths are chosen to be around 8 nm so that the separation between the lowest ($e1$) and the second ($e2$) conduction subbands matches the photon energy range of a CO₂-laser^{13,33,34}. In order to correlate the spectral dependence of the photocurrent to the absorption of the QWs, optical transmission measurements have been performed using a Fourier transform infrared spectrometer. Direct inter-subband optical transitions in n -type GaAs QWs are obtained by applying various wavelengths of a line tunable Q-switched as well as an transversal excited atmospheric pressure (TEA) CO₂-lasers (see, e.g.,^{3,35}). The lasers yield linearly polarized radiation at wavelengths λ between $9.2 \mu\text{m}$ and $10.8 \mu\text{m}$ corresponding to photon energies $\hbar\omega$ ranging from 135 meV to 114 meV. The Q-switched laser has a peak power of 2 kW at a repetition rate of 300 Hz.

The samples are irradiated at normal incidence, i.e. along the growth direction, as well as at oblique incidence with an angle θ_0 between the light propagation direction and the QW growth direction z . We use here Cartesian coordinates $x \parallel [1\bar{1}0]$, $y \parallel [110]$, $z \parallel [001]$. The external magnetic field \mathbf{B} up to 1 T is applied parallel to the interface plane along the x or y directions. In order to vary the angle between the polarization vector of the linearly polarized light and the magnetic field, we place a linear polarizer, made of two Brewster windows, behind a Fresnel rhomb. After passing through the Fresnel rhomb initially linearly polarized laser light becomes circularly polarized. Rotation of the linear polarizer enables us to obtain linearly polarized radiation with angle $\alpha = 0^\circ \div 360^\circ$ between the vector of light polarization and the incidence plane.

To measure electric currents, two pairs of Ohmic contacts have been centered at opposite

sample edges oriented along x and y (see Fig. 1(c)). The photocurrent J generated in the unbiased devices is measured via the voltage drop across a $50\ \Omega$ load resistor in a closed circuit configuration (see Fig. 1(c)). The voltage in response to a laser pulse is recorded with a fast storage oscilloscope.

Irradiation of samples with normally incident linearly polarized radiation in the absence of an external magnetic field causes no photocurrent. This result agrees with the phenomenological theory which does not allow any photocurrent at homogeneous excitation of structures belonging to D_{2d} or C_{2v} point-group symmetries relevant to (001)-grown GaAs QW structures¹⁻³. A photocurrent response is obtained only when a magnetic field \mathbf{B} is applied. The signal is detected only in the direction perpendicular to the orientation of the magnetic field independent whether \mathbf{B} is aligned along x or y . The basic features of the signals remain the same in both geometries, therefore, in the following, we give only results for photocurrents measured in the x direction and magnetic field oriented along y . The signal follows the temporal structure of the laser pulse and changes the sign upon inversion of the magnetic field direction from $B_y > 0$ to $B_y < 0$. Signal traces are shown in Fig. 1 compared to records of a linear photon drag detector³. Besides the experimental geometry with normal incidence of the radiation on the samples, the magnetic field induced photocur-

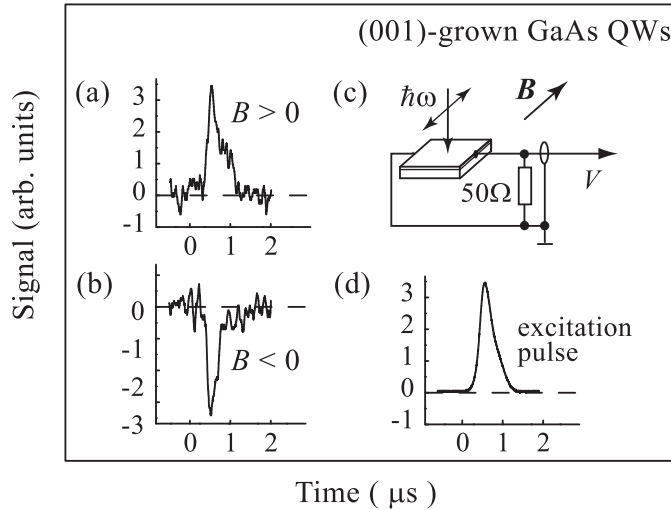


FIG. 1: Oscilloscope traces obtained for pulsed excitation of (001)-grown n -type GaAs QWs at $\lambda = 10.27\ \mu\text{m}$. Figures (a) and (b) show magneto-gyrotropic photogalvanic signals obtained for magnetic fields $B_y = 0.3\ \text{T}$ and $B_y = -0.3\ \text{T}$, respectively. For comparison in (d) a signal pulse of a fast photon drag detector is plotted. In (c) the measurement arrangement is sketched.

rent has also been observed at oblique incidence. We note that the excitation of QWs at oblique incidence results in a measurable electric current even at zero magnetic field due to the linear photogalvanic and photon drag effects³. In this work we examine magnetic field induced photocurrents J_x^{MPGE} only, i.e., currents which reverse their sign upon switching the magnetic field direction. In order to extract such a current contribution from the measured total current we determine the response to the magnetic field aligned along the y axis, B_+ , and along $-y$, B_- , and evaluate the data after

$$J_x^{MPGE} = [J_x(B_+) - J_x(B_-)] / 2. \quad (1)$$

Magnetic field and polarization dependencies of J_x^{MPGE} are presented in Figs. 2 and 3. As is shown in Fig. 2, the photocurrent exhibits linear dependence on the magnetic field strength in all investigated samples. Figure 3 demonstrates the essential difference between the magnetic field induced photocurrents excited at normal and at oblique incidence. While at normal incidence the current is almost independent of the radiation polarization, at

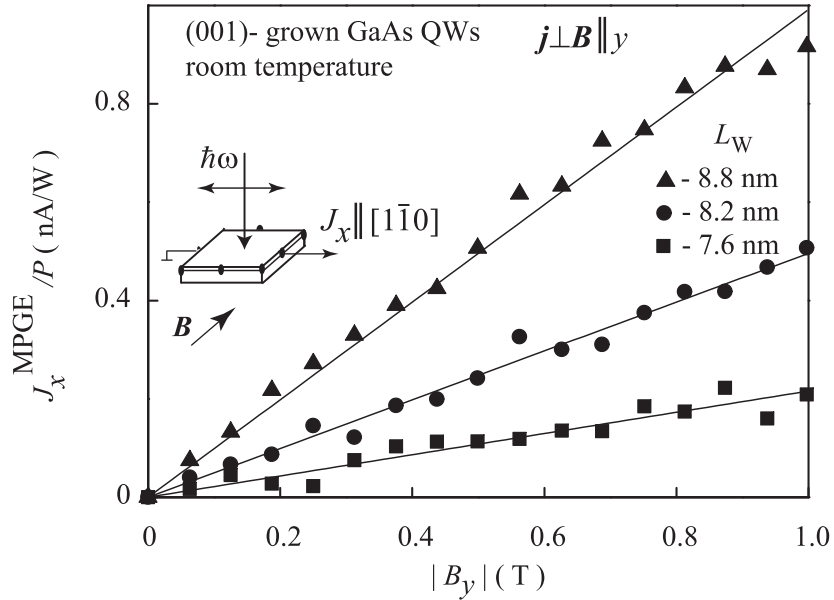


FIG. 2: Magnetic field dependence of the photocurrent measured in (001)-grown GaAs QWs structures of various widths on the magnetic field \mathbf{B} parallel to the $[110]$ axis. Optical excitation of $P \approx 1$ kW at normal incidence is applied at three different wavelengths corresponding to the signal maximum in each QW, see arrows in Fig. 5 (λ_1 for QW with $L_W = 8.8$ nm, λ_2 for $L_W = 8.2$ nm and λ_3 for $L_W = 7.6$ nm). The current is measured in the direction perpendicular to \mathbf{B} and for radiation polarized perpendicular to \mathbf{B} .

oblique incidence the magneto-induced photocurrent gets polarization-dependent: it reaches maximum for the radiation polarized in the incidence plane (p -polarization, $\alpha = 0^\circ$) and minimum for the orthogonal polarization where radiation electric field has no component normal to the QW plane (s -polarization, $\alpha = 90^\circ$).

Figure 4 shows the spectral dependences of the photocurrent obtained in the range of photon energies accessible with the CO₂-lasers. The data are obtained at normal incidence for a constant magnetic field $B = 0.3$ T in QW structures of various QW widths L_W . It is seen that the photocurrent has a resonant character and the peak of the resonance shifts to the higher energies for narrower QWs. In Fig. 5 the observed current for a sample with QWs of 8.8 nm width is plotted as a function of photon energy $\hbar\omega$ together with the absorption spectrum. The spectral dependence of the photocurrent corresponds to that of inter-subband absorption measured by means of the Fourier transform infrared spectroscopy and can be well fitted by a Lorentzian. The photocurrent resonance shifts to shorter wavelength (blue

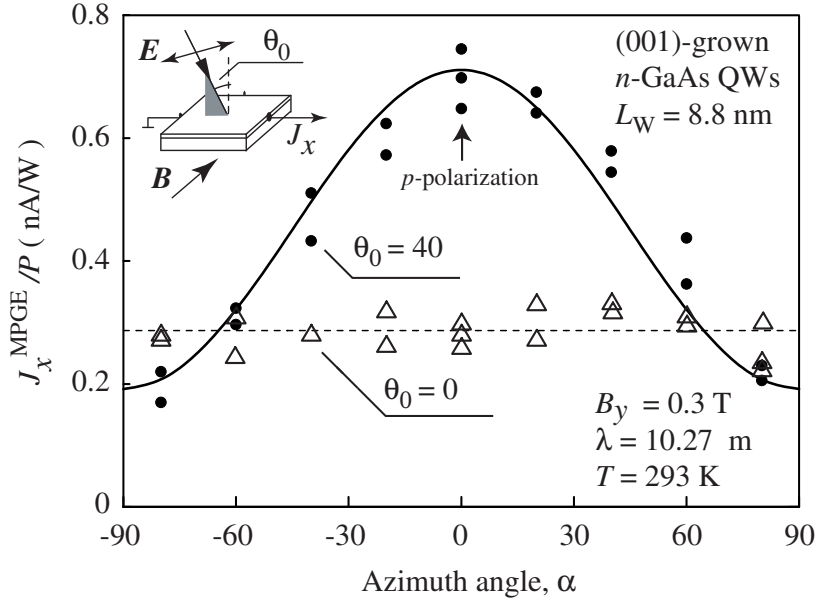


FIG. 3: Dependences of the magneto-induced photocurrent J_x^{MPGE} normalized by the power P on the azimuth angle α of the light polarization plane measured at normal incidence ($\theta_0 = 0^\circ$) and at oblique incidence ($\theta_0 = 40^\circ$). In the latter case the plane of incidence is the (xz) plane. Azimuth angle $\alpha = 0^\circ$ corresponds to the maximum value of the electric field component normal to the QW plane (p -polarization). Solid and dashed curves are fits by an analytical expression given by Eq. (3) taking into account the light refraction and absorption in QW structure (see Eq. (2)).

shift) and narrows if the temperature is reduced from room to liquid helium temperature. All the observed features, the coincidence of the photocurrent and the absorbance spectra, the shift of the spectral position of the photocurrent resonance by variation of the QW width, as well its temperature behaviour demonstrate that the observed photocurrent is caused by the inter-subband transitions.

Now we analyze the dependence of the MPGE photocurrent on the angle of incidence θ_0 and the azimuth angle α considering that the QW structure represents a absorbing uniaxial medium with the optical axis perpendicular to the structure surface. We assume that in the investigated samples the anisotropy of the refractive index is sufficiently small ($n_z \approx n_{\parallel} \approx n$), but the anisotropy of the absorbance is strong ($\eta_z \gg \eta_{\parallel}$), where the subscripts z and \parallel correspond to the radiation polarized along the growth direction z and parallel to the QW plane, respectively. In the case of linearly polarized radiation, the polarization dependence

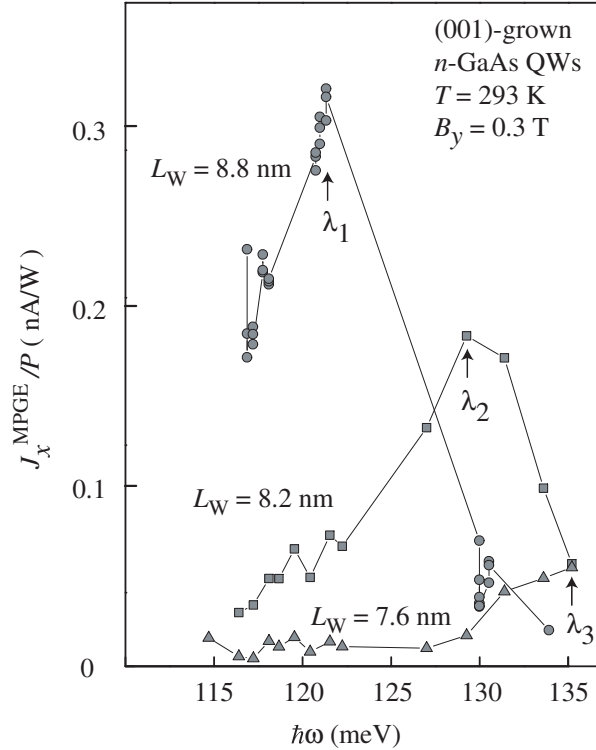


FIG. 4: Spectral dependences of the magneto-induced photocurrent J_x^{MPGE} normalized by the power P at the magnetic field $B_y = 0.3$ T. The dependences are measured for three (001)-grown GaAs/AlGaAs samples with various QW widths under normal incidence of the light at room temperature. Arrows indicate wavelengths used in Fig. 2.

of the structure absorbance $\eta(\alpha, \theta)$ following to Ref.³⁶ and Fresnel laws is described by

$$\eta(\alpha, \theta) = t_p^2 \cos^2 \alpha (\eta_{\parallel} \cos^2 \theta + \eta_z \sin^2 \theta) + t_s^2 \eta_{\parallel} \sin^2 \alpha, \quad (2)$$

where θ is the refraction angle in the QW structure, $\sin \theta = \sin \theta_0 / n$, t_p and t_s are the transmission coefficients through the sample surface for p - and s -polarized components of the light electric field, respectively³⁷.

We suppose that the polarization dependence of the MPGE current density is determined solely by the polarization dependence of the radiation absorbance and, therefore, has the form

$$j_x^{MPGE} = \gamma B_y \frac{nc}{4\pi} E_0^2 \eta(\alpha, \theta), \quad (3)$$

where γ is a parameter, E_0 is the electric field amplitude of incident light and c is the light velocity. While in the experiments the electric current J_x^{MPGE} is measured, in the theoretical consideration the current density j_x^{MPGE} is used which is proportional to the current J_x^{MPGE} . We fit the measured polarization dependence of the photocurrent by Eqs. (2) and (3) using, besides the ordinate scaling parameter γ , the ratio η_z/η_{\parallel} as a fitting parameter. Figure 3 shows that the MPGE data can be fitted well by Eq. (2) for $\eta_z/\eta_{\parallel} \approx 50$ supporting the

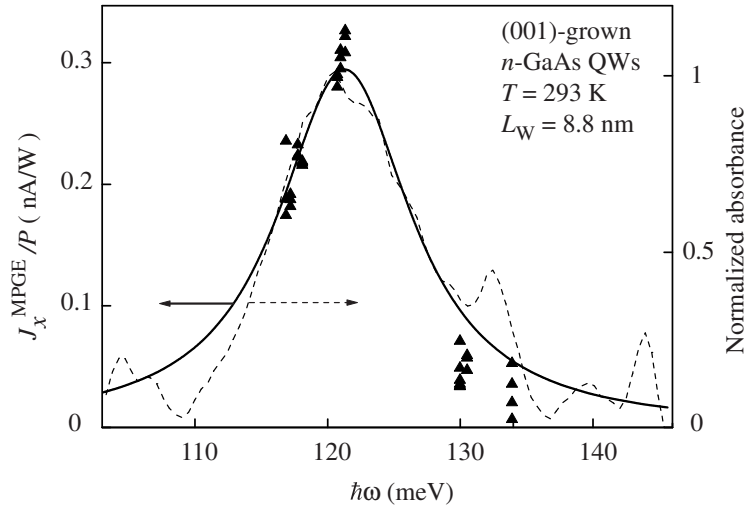


FIG. 5: Spectral dependence of the magneto-induced photocurrent J_x^{MPGE} normalized by the power P at the magnetic field $B_y = 0.3$ T. The current is measured under normal incidence of the light at room temperature. Solid curve is fit to experimental data (triangles) by a Lorentz function. The dashed curve shows the normalized absorbance spectrum measured in the multiple pass geometry.

assumption that the polarization dependence of the photocurrent can solely be described by the polarization dependence of absorption.

As demonstrated above, in our experiments the current is caused by direct inter-subband transitions which are usually supposed to be excited by light with the polarization vector having a nonzero component normal to the QW plane only (for review see³⁸). In our consideration the corresponding absorbance is η_z . The inter-subband absorption of light polarized parallel to the QW plane η_{\parallel} is generally expected to vanish because these transitions are forbidden by the dipole selection rules. However, these rules are valid in the framework of the simple one-band model only^{39,40} and it has been experimentally demonstrated that they are not rigorous⁴¹. Our data support this conclusion and show that the absorbance of light with the polarization vector parallel to the QW plane can be as large as 2 % of the absorbance of the light polarized along the QW growth direction.

II. PHENOMENOLOGICAL ANALYSIS

The MPGE in zinc-blende-type QWs is related to the gyrotropic properties of the structures. The gyrotropic point group symmetry makes no difference between components of axial and polar vectors, and hence allows an electric current $j_{\alpha} \propto IB_{\beta}$, where I is the light intensity inside the sample and B_{β} are components of the applied magnetic field. Photocurrents which require simultaneously gyrotropy and the presence of a magnetic field are gathered in a class of magneto-optical phenomena denoted as magneto-gyrotropic photogalvanic effects^{2,3}.

The dependence of the photocurrent direction on the light polarization and orientation of the magnetic field with respect to the crystallographic axes may be obtained from symmetry considerations which do not require knowledge of the microscopic origin of the effect. Particularly, the MPGE current in response to linearly polarized radiation and within the linear regime in the magnetic field is given by^{2,3,23}

$$j_{\alpha} = \sum_{\beta\gamma\delta} \phi_{\alpha\beta\gamma\delta} B_{\beta} \frac{E_{\gamma}E_{\delta}^{*} + E_{\delta}E_{\gamma}^{*}}{2}, \quad (4)$$

where ϕ is a fourth-rank pseudotensor symmetric in the last two indices, $\phi_{\alpha\beta\gamma\delta} = \phi_{\alpha\beta\delta\gamma}$, and E_{γ} are components of the electric field of the radiation wave in the structure.

We focus on QWs of the C_{2v} symmetry, which corresponds to asymmetrically doped

(001)-oriented GaAs QW structures studied in our experiments. In structures of such a symmetry, components of the MPGE current for, e.g., $\mathbf{B} \parallel y$ are described by

$$j_x = [C_1(e_x^2 + e_y^2) + C_2(e_x^2 - e_y^2) + C_3 e_z^2] B_y I, \quad (5)$$

$$j_y = C_4 e_x e_y B_y I, \quad (6)$$

where (e_x, e_y, e_z) are components of the unit polarization vector \mathbf{e} inside the medium, \mathbf{e} is assumed to be real for the linearly polarized radiation; I is the light intensity inside the medium related to the electric field of the incident light E_0 by $I = (ncE_0^2/4\pi)[(t_s^2 - t_p^2) \sin^2 \alpha + t_p^2]$; $C_1 \div C_4$ are linearly independent coefficients that can be non-zero in QWs of the C_{2v} symmetry, they are related to components of the tensor $\phi_{\alpha\beta\gamma\delta}$ by $C_1 \propto (\phi_{xyxx} + \phi_{xyyy})/2$, $C_2 \propto (\phi_{xyxx} - \phi_{xyyy})/2$, $C_3 \propto \phi_{xyzz}$, $C_4 \propto 2\phi_{yyxy} = 2\phi_{yyyx}$.

The fact that at normal incidence ($e_z = 0$, $e_x^2 + e_y^2 = 1$) we observed only a polarization-independent photocurrent in the direction perpendicular to the magnetic field demonstrates that the coefficients C_2 and C_4 in the present experiments are negligibly small as compared to C_1 . At oblique incidence, the polarization-dependent current contribution determined by the coefficient C_3 is also detected. We found from experiment that $C_3 \gg C_1$. Such a behaviour is similar to the polarization dependence of the QW absorbance η where, in accordance with Eq. (2), the radiation polarized in the QW plane causes weaker optical transitions than that having nonzero out-of-plane component of the polarization vector. As has been shown \mathbf{j} can be described solely by the polarization dependence of η . In this model the parameters C_1 and C_3 in the phenomenological expression Eq. (5) are given by $C_1 = \gamma\eta_{\parallel}$ and $C_3 = \gamma\eta_z$.

III. MICROSCOPIC THEORY

Microscopically, the magneto-gyrotropic photocurrents in QW structures can be of both spin-dependent as well as spin-independent origin. The proposed spin-dependent mechanisms of photocurrents include asymmetry of direct optical transitions between Rashba-Dresselhaus spin-split branches of the lowest electron subband^{27,28,42}, spin-dependent asymmetry of the scattering-assisted radiation absorption by free carriers (Drude absorption)²⁵, and spin-dependent energy relaxation of the electron gas heated by the radiation^{25,26,43}.

The spin-independent mechanisms reported so far comprise magnetic field induced photocurrents caused by a diamagnetic shift of energy bands^{29–32,38} and diamagnetic corrections to electron-phonon interaction^{44,45}. In this Section we consider step by step various microscopic mechanisms which can contribute to the photocurrent induced by optical transitions between the quantum subbands $e1$ and $e2$ in the presence of an in-plane magnetic field. We assume for simplicity that the photocurrent is excited at oblique incidence of p -polarized radiation. This particular case can be described in a simple single-band model where only the e_z component of the polarization vector induces inter-subband optical transitions. In the phenomenological theory this contribution to the current corresponds to the last term on the right hand side of Eq. (5) proportional to the parameter C_3 .

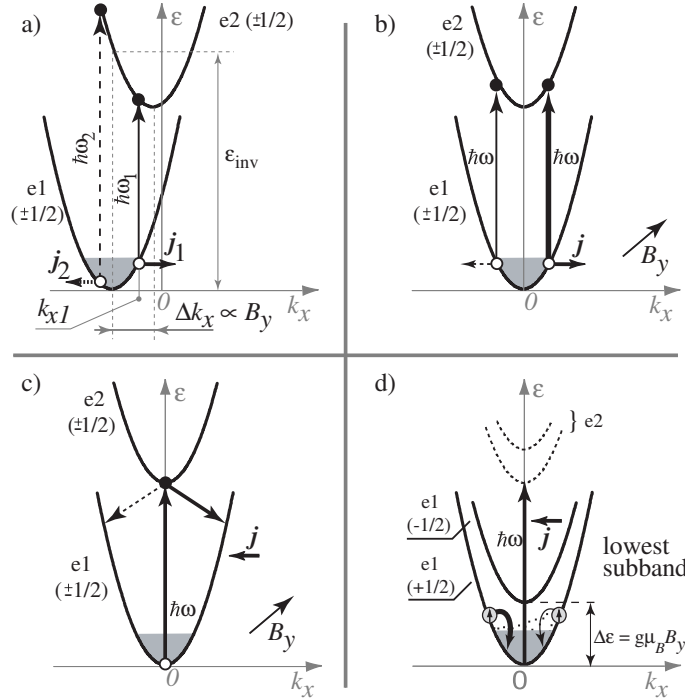


FIG. 6: Microscopic models of MPGE current formation at inter-subband transitions. (a) and (b): Current induced by asymmetric optical excitation due to (a) diamagnetic shift of subbands in \mathbf{k} -space, (b) linear-in- \mathbf{k} diamagnetic terms in the optical transition matrix elements. (c) and (d): Current induced by asymmetric free carrier relaxation due to (c) \mathbf{k} -linear diamagnetic terms in the scattering amplitude, (d) spin-dependent asymmetry of energy relaxation.

A. Diamagnetic mechanisms of the MPGE caused by inter-subband optical transitions in quantum wells

Diamagnetic mechanisms of the MPGE are related to the influence of the in-plane magnetic field on the orbital motion of carriers rather than on the electron spin. Microscopically, these mechanisms originate from the Lorentz force, which pushes electrons to the right or the left interface depending on their direction of velocity and, therefore, changes the electron wave function and energy. Since the Lorentz force is proportional to the magnetic field and the electron velocity, the resulting small diamagnetic corrections to the wave function and energy are linear in \mathbf{k} as well as linear in \mathbf{B} .

Below, again for simplicity, we consider only linear-in- \mathbf{k} corrections caused by structure inversion asymmetry. The corresponding contribution to the effective Hamiltonian induced by the in-plane magnetic field has the form³⁸

$$H_{dia} = \frac{\hbar e}{m^* c} (B_x k_y - B_y k_x) z, \quad (7)$$

where e is the electron charge, m^* is the effective electron mass, B_x and B_y are components of the magnetic field, and z is the coordinate operator. The Hamiltonian Eq. (7) corresponds to the vector potential $\mathbf{A} = (B_y z, -B_x z, 0)$, $\mathbf{B} = \text{rot} \mathbf{A}$.

1. Current due to \mathbf{k} -linear diamagnetic shift of subbands

It is a well known fact that an in-plane magnetic field applied to an asymmetric 2D electron gas induces a spin-independent diamagnetic shift of the electron spectrum in \mathbf{k} -space in each size-quantized subband³⁸. The corresponding corrections to the electron energies are determined by the diagonal matrix elements of the Hamiltonian (7) and have the form

$$\delta\varepsilon_\nu = \frac{\hbar e}{m^* c} (B_x k_y - B_y k_x) z_{\nu\nu}, \quad (8)$$

where ν is the subband index, $z_{\nu\nu} = \int \varphi_\nu^2(z) z dz$ is the coordinate matrix element, φ_ν is the function of size quantization in the subband ν in zero magnetic field. This situation is sketched in Fig. 6(a) for $e1$ and $e2$ subbands. We note that, in spite of the fact that in gyrotropic QWs the spin degeneracy is removed even in the absence of an external magnetic field, we neglect both the zero-field spin-splitting and the Zeeman spin-splitting in the

description of diamagnetic mechanisms of the current formation. The value of the diamagnetic shift depends on $z_{\nu\nu}$ and is generally different for $e1$ and $e2$ subbands. Due to the relative shift of the two subbands $\Delta k_x \propto B_y$, the inter-subband optical transitions induced by the monochromatic radiation of the photon energy $\hbar\omega_1$ occur only at a fixed wave vector k_{x1} where the energy of the incident light matches the transition energy as it is indicated by the solid vertical arrow in Fig. 6(a). Therefore, optical transitions generate an imbalance of momentum distribution in both subbands yielding an electric current. However, a non-equilibrium distribution of carriers in the upper subband rapidly relaxes due to the very effective relaxation channel of LO -phonon emission, because the energy of the intersubband optical transition is well above the energy of LO -phonons in n -GaAs QWs ($\hbar\Omega_{LO} \approx 35$ meV). Thus, the contribution of the $e2$ subband to the electric current vanishes and the electron flow is determined by the momentum distribution of carriers in the lowest subband. As directly follows from this model picture, the variation of the incident light frequency causes the inversion of the current direction. At small photon energy, $\hbar\omega_1 < \varepsilon_{inv}$, excitation occurs at k_{x1} shifted to the right from the $e1$ minimum resulting in a current j_x shown by the solid arrow in Fig. 6(a). The increase of the photon energy shifts the transition toward negative k_x ($\hbar\omega_2 > \varepsilon_{inv}$, dashed vertical arrow in Fig. 6(a)) and reverses the direction of the current shown by the dashed horizontal arrow. The inversion of the current sign occurs at the photon energy $\hbar\omega = \varepsilon_{inv}$ corresponding to the optical transitions at the minimum of $e1$.

Calculations show that, for the case of optical transitions between the subbands $e1$ and $e2$ and the magnetic field aligned along y , this contribution to the photocurrent has the form

$$j_x = (z_{11} - z_{22}) \frac{e^2 B_y}{m^* c} \left[\tau_p^{(2)} \eta(\hbar\omega) + (\tau_p^{(1)} - \tau_p^{(2)}) \bar{\varepsilon} \frac{d \eta(\hbar\omega)}{d \hbar\omega} \right] \frac{I}{\varepsilon_{21}}, \quad (9)$$

where $\tau_p^{(1)}$ and $\tau_p^{(2)}$ are the momentum scattering times in the subbands, $\eta(\hbar\omega)$ is the QW absorbance, which is calculated neglecting \mathbf{k} -linear terms but taking into account the inhomogeneous spectral broadening of the inter-subband resonance, ε_{21} is the energy separation between the subbands $e1$ and $e2$, and $\bar{\varepsilon}$ is the average electron kinetic energy. The latter equals to $k_B T$ and $E_F/2$ for a non-degenerate and degenerate two-dimensional electron gas, respectively, where T is the temperature and E_F is the Fermi energy.

In accordance to general symmetry arguments, the MPGE current given by Eq. (9) is related to the structure inversion asymmetry of the QW and vanishes in symmetric structures where $z_{11} = z_{22}$. From Eq. (9) follows that, for the relaxation time of carriers in the

excited subband much shorter than that in the ground subband, $\tau_p^{(2)} \ll \tau_p^{(1)}$, the current contribution due to the diamagnetic shift of the electron subbands is proportional to the spectral derivative of the QW absorbance. This is similar to the spectral behaviour of the linear^{9,10} and circular¹¹ photon drag effects as well as the circular photogalvanic^{13,46} effect caused by inter-subband transitions in n -doped QW structures.

2. Current due to \mathbf{k} -linear diamagnetic terms in the matrix element of optical transitions

In the previous Section we considered the photocurrent caused by linear-in- \mathbf{k} and linear-in- \mathbf{B} terms in the energy spectrum yielding the diamagnetic shift of subbands. Another diamagnetic contribution to the MPGE, which does not rely on a band shift, comes from the diamagnetic terms in the matrix element of inter-subband optical transitions M . These terms are also linear in \mathbf{k} and \mathbf{B} and result in different probabilities of optical transitions for positive and negative k_x . Indeed, the in-plane magnetic field intermixes the electron states from the different subbands that leads to asymmetric terms in the matrix element of optical transitions. This is depicted in Fig. 6(b) by vertical arrows of different thickness. This process leads to an asymmetric distribution of carriers in \mathbf{k} -space, i.e. to an electrical current. Again the contribution of the upper subband to the current can be ignored due to rapid relaxation by emission of optical phonons.

In first order perturbation theory, the wave functions of size quantization have the form

$$\varphi_{\nu,\mathbf{k}}(z) = \varphi_{\nu}(z) + (B_x k_y - B_y k_x) \frac{\hbar e}{m^* c} \sum_{\nu' \neq \nu} \frac{z_{\nu'\nu}}{\varepsilon_{\nu\nu'}} \varphi_{\nu'}(z), \quad (10)$$

where $\varepsilon_{\nu\nu'} = \varepsilon_{\nu} - \varepsilon_{\nu'}$ is the energy separation between the subbands. We note that the functions given by Eq. (10) with different ν remain orthogonal at any wave vector \mathbf{k} and, therefore, the selection rules for inter-subband optical transitions are preserved. However, the in-plane magnetic field adds \mathbf{k} -linear terms to the matrix element of optical transitions between the subbands $e1$ and $e2$. This matrix element can be written as

$$M = M_0 \left[1 + (B_x k_y - B_y k_x) \frac{\hbar e}{m^* c} \sum_{\nu \neq 1,2} \left(\frac{z_{\nu 1}}{\varepsilon_{\nu 1}} \frac{p_{\nu 2}}{p_{21}} - \frac{z_{\nu 2}}{\varepsilon_{\nu 2}} \frac{p_{\nu 1}}{p_{21}} \right) \right], \quad (11)$$

where $M_0 \propto p_{21} e_z$ is the matrix element of the transitions in zero field, $p_{\nu\nu'} = \int \varphi_{\nu}(z) p_z \varphi_{\nu'}(z) dz$ is the matrix element of the momentum operator.

The \mathbf{k} -linear terms in the matrix element of the optical transitions (11) give rise to an imbalance in the carrier distribution between positive and negative wave vectors in both $e1$ and $e2$ subbands, leading to a net electric current. Calculation shows that the corresponding electric current for the magnetic field \mathbf{B} aligned along the y axis is given by

$$j_x = 2(\tau_p^{(1)} - \tau_p^{(2)}) \bar{\varepsilon} \frac{e^2 B_y}{m^* c} \sum_{\nu \neq 1,2} \left(\frac{z_{\nu 1} p_{\nu 2}}{\varepsilon_{\nu 1} p_{21}} - \frac{z_{\nu 2} p_{\nu 1}}{\varepsilon_{\nu 2} p_{21}} \right) \frac{I \eta (\hbar \omega)}{\varepsilon_{21}}. \quad (12)$$

The photocurrent given by Eq. (12) is present only in asymmetric QWs. In symmetric QWs, where the wave functions $\varphi_\nu(z)$ are either even or odd, the current vanishes because the products $z_{\nu 1} p_{\nu 2}$ and $z_{\nu 2} p_{\nu 1}$ are zero for any ν . In contrast to the mechanism considered in Section III A 1, the spectral behaviour of the photocurrent caused by \mathbf{k} -linear terms in the optical matrix element follows the QW absorbance. However, estimations show that the contribution described by Eq. (12) is less than the photocurrent due to the diamagnetic shift of the subbands given by Eq. (9) and, thus, can not be responsible for the observed MPGE.

3. Current due to \mathbf{k} -linear diamagnetic terms in the scattering amplitude

Besides the asymmetry of optical transitions considered above, an asymmetry of the subsequent relaxation processes of photocarriers can also cause an electric current. The relaxation processes following the intersubband optical excitation include two steps: electron scattering back from the excited $e2$ to the lower $e1$ subband and subsequent relaxation to the equilibrium within the $e1$ subband. The former step, electron scattering to the lower subband, is depicted in Fig. 6(c) by tilted downward arrows. In gyrotropic quantum wells subjected to an external magnetic field, the matrix element of inter-subband scattering by static defects or phonons contains an additional term proportional to $(B_x k_y - B_y k_x)$. Therefore, the scattering rates to final states with positive and negative wave vectors k_x become different as reflected in Fig. 6(c) by arrows of different thickness. Such an imbalance caused by asymmetry of the scattering results in an electric current in the ground subband which is proportional to the applied magnetic field.

To estimate this current contribution we neglect diamagnetic shifts of the subbands and consider electron scattering from the state in the second subband bottom ($e2, 0$) to the state in ground subband ($e1, \mathbf{k}$) assisted by the most efficient process here of an optical phonon emission. Taking into account the form of the electron wave functions in the subbands [see

Eq. (10)], one can derive the matrix element of inter-subband scattering. For the Frölich mechanism of electron-phonon interaction², it has the form

$$V_{e1,\mathbf{k};e2,0}^{(+)} = \frac{C}{q} \left[Q_{12}(q_z) + (B_x k_y - B_y k_x) \frac{\hbar e}{m^* c} \sum_{\nu \neq 1} \frac{z_{\nu 1}}{\varepsilon_{1\nu}} Q_{2\nu}(q_z) \right] \delta_{\mathbf{k}, -\mathbf{q}_{\parallel}}, \quad (13)$$

where C is a parameter depending on the material, $Q_{\nu\nu'}(q_z) = \int \varphi_{\nu}(z) \varphi_{\nu'}(z) \exp(-iq_z z) dz$, $\mathbf{q} = (\mathbf{q}_{\parallel}, q_z)$ is the wave vector of the phonon involved, $\mathbf{q}_{\parallel} = -\mathbf{k}$, $k = |\mathbf{k}|$, and $k = \sqrt{2m^*(\varepsilon_{21} - \hbar\Omega_{LO})/\hbar}$ due to the energy and the in-plane quasi-momentum conservation.

The matrix element of inter-subband scattering (13) contains \mathbf{k} -linear terms which lead to asymmetric distribution of carriers in the ground subband. Calculation shows that the corresponding electric current for the magnetic field \mathbf{B} aligned along the y axis has the form

$$j_x = 2\tau_p^{(1)} \frac{e^2 B_y}{m^* c} \left(1 - \frac{\hbar\Omega}{\varepsilon_{21}} \right) \sum_{\nu \neq 1} \frac{z_{\nu 1} \zeta_{\nu}}{\varepsilon_{\nu 1}} I\eta(\hbar\omega), \quad (14)$$

where

$$\zeta_{\nu} = \frac{\int \int \varphi_1(z) \varphi_2(z) \varphi_2(z') \varphi_{\nu}(z') \exp(-|z - z'|k) dz dz'}{\int \int \varphi_1(z) \varphi_2(z) \varphi_1(z') \varphi_2(z') \exp(-|z - z'|k) dz dz'}. \quad (15)$$

We note that in this mechanism values of k can be large compared to that in the mechanism of Section III A 2. Similarly to the previous mechanisms of the MPGE, the current due to asymmetry of scattering (14) is present only in asymmetric QWs where the products $z_{\nu 1} \zeta_{\nu}$ do not vanish. We also pointed out that processes of energy relaxation of electrons within the ground subband, which follow the intersubband scattering, are also asymmetrical in the presence of in-plane magnetic field^{44,45} and contribute to the current.

The spectral dependence of relaxation currents repeats that of the QW absorbance $\eta(\hbar\omega)$ which is reasonable for all mechanisms where details of optical excitation are lost. Estimations show that these mechanisms can predominate in real structures and determine the MPGE behaviour.

B. Spin-related mechanisms

This group of the MPGE mechanisms is based on spin-dependent asymmetry of photoexcitation and/or relaxation in the gyrotropic QWs with equilibrium spin polarization due to the Zeeman effect. Two spin-related current contributions considered below follow the spectral dependence of the QW absorbance $\eta(\hbar\omega)$.

1. Current due to spin-dependent asymmetry of energy relaxation

This mechanism is considered in detail in^{25,26} for electron gas heated by the Drude-like absorption of the THz radiation. The mechanism is based on the process of energy relaxation and, therefore, does not relate on details of optical excitation, besides the strength of absorption and processes involved in the energy relaxation.

Figure 6(d) sketches the basic physics of this mechanism. In the considered case of the radiation absorption due to direct inter-subband transitions electrons excited to the $e2$ subband first return to the ground subband and then rapidly lose their energy by the emission of optical phonons. After the emission of optical phonons the energy of electrons gets smaller than $\hbar\Omega_{LO}$ and the relaxation continues due to the emission of acoustic phonons. Due to the Zeeman effect, the lowest subband is split into two spin branches which are unequally occupied. For simplicity Fig. 6(d) sketches the process of energy relaxation of hot electrons for only the lowest spin-up branch ($s = +1/2$). Energy relaxation processes are shown by curved arrows. Usually, energy relaxation via scattering of electrons is considered to be spin-independent. In gyrotropic media, however, spin-orbit interaction adds asymmetric spin-dependent term to the scattering probability. These terms in the scattering matrix element are proportional to components of $[\boldsymbol{\sigma} \times (\mathbf{k} + \mathbf{k}')]_z$, where $\boldsymbol{\sigma}$ is the vector composed of the Pauli matrices, \mathbf{k} and \mathbf{k}' are the initial and scattered electron wave vectors in the ground subband (we consider here only the spin-dependent contribution induced by heteropotential asymmetry). Due to spin-dependent scattering, transitions to positive and negative k'_x -states occur with different probabilities. Therefore hot electrons with opposite k_x within one branch have different relaxation rates. In Fig. 6(d) this difference is indicated by arrows of different thickness. This in turn yields a net electron flow, $\mathbf{i}_{\pm 1/2}$, within each spin branch. Since the asymmetric part of the scattering amplitude depends on spin orientation, the probabilities for scattering to positive or negative k'_x -states are inverted for spin-down and spin-up branches. Without magnetic field, the charge currents $\mathbf{j}_+ = e\mathbf{i}_{+1/2}$ and $\mathbf{j}_- = e\mathbf{i}_{-1/2}$ have opposite directions because $\mathbf{i}_{+1/2} = -\mathbf{i}_{-1/2}$ and cancel each other. However, the external magnetic field changes the relative population of spin branches and, therefore, lifts the balance between \mathbf{j}_+ and \mathbf{j}_- yielding a net electric current. The photocurrent magnitude can be estimated as

$$j \sim e\tau_p^{(1)} S^{(0)} \frac{\xi}{\hbar} I \eta(\hbar\omega), \quad (16)$$

where $S^{(0)} = g\mu_B B / (4k_B T)$ is the equilibrium spin polarization for the Boltzmann distri-

bution, and ξ is a parameter standing for the ratio of spin-dependent to spin-independent parts of electron-phonon interaction.

2. Current due to asymmetry of spin relaxation (*spin-galvanic effect*)

For completeness we also give an estimation for the second possible spin-dependent mechanism, previously considered by us in Ref.²⁴. It is based on the asymmetry of spin-flip relaxation processes and represents in fact the spin-galvanic effect¹² where the current is linked to non-equilibrium spin polarization

$$j_i = Q_{ii'}(S_{i'} - S_{i'}^{(0)}) . \quad (17)$$

Here \mathbf{S} is the average non-equilibrium electron spin and $\mathbf{S}^{(0)}$ is its equilibrium value, see Eq. (16). In contrast to the mechanisms considered in Sections III A 1-III A 3 this mechanism requires spin-flip processes together with a *non-equilibrium* spin polarization. A *non-equilibrium* spin polarization results from the photoinduced depolarization of electron spins in the system with equilibrium polarization caused by the Zeeman effect. Indeed, due to the fact that in equilibrium electrons preferably occupy the lower spin branch, optical transitions, being proportional to the electron concentration, predominantly excite this branch. These optically excited electrons under energy relaxation return to both spin branches resulting in non-equilibrium population of the branches. The following spin relaxation results in the spin-galvanic current (see Ref.¹²).

An estimation of this photocurrent for the D'yakonov-Perel spin relaxation mechanism yields

$$j \sim e\tau_p^{(1)} S^{(0)} \frac{\beta^{(1)}}{\hbar} \frac{I\eta(\hbar\omega)}{\varepsilon_{21}} , \quad (18)$$

where β is the constant of \mathbf{k} -linear spin-orbit splitting of the subband $e1$.

IV. CONCLUSIONS

Summarizing our experiments and the microscopic theory developed here we emphasize that the resonance spectral behaviour of the observed magnetic field induced photocurrent following the inter-subband absorption profile proves that the photocurrent is due to direct

inter-subband transitions. As an interesting feature, the resonant photocurrent is also detected at normal incidence of the radiation on (001)-grown QWs. This result demonstrates that the selection rules conventionally applied for inter-subband optical transitions are not rigorous. Considering that the photocurrent is proportional to the QW absorbance, we obtain from the experiment that the ratio of absorbance for light polarized along the growth direction z and in the QW plane is $\eta_z/\eta_{\parallel} \approx 50$. Surprisingly, the MPGE photocurrent is not caused by the diamagnetic shift of subbands (see Section III A 1). Such a current has been previously reported for inter-band absorption and is expected to be strong compared to spin-dependent mechanism because of its non-relativistic nature. However, the absence of spectral inversion of the photocurrent at intersubband absorption resonance unambiguously rules out this mechanism. Three other possible mechanisms of current formation developed here cannot be distinguished qualitatively. Based on quantitative estimations of the mechanisms given in Sections from III A 2 to III B 2 we attribute the MPGE current to \mathbf{k} -linear diamagnetic terms in the scattering matrix element yielding asymmetric relaxation of carriers in \mathbf{k} -space (Section III A 3). Finally we note that diamagnetic and spin-dependent mechanisms might be qualitatively distinguished in structures where the g -factor can be varied like in dilute semimagnetic materials. Indeed, while spin-dependent mechanisms are proportional to the g -factor, diamagnetic mechanisms are independent of the Zeeman splitting.

Acknowledgements

We thank E.L. Ivchenko for helpful discussions. This work was supported by the Deutsche Forschungsgemeinschaft through GA 501/6, SFB 689, SPP 1285, the RFBR, programs of the RAS and Russian Ministry of Education and Science, Russian President Grant for young scientists, and the Russian Science Support Foundation.

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